## Commission Briefing Paper 4D-01

# Potential Impacts of Climate Change on Surface Transportation Infrastructure Design

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Date: January 30, 2007

### Introduction

This paper is part of a series of briefing papers to be prepared for the National Surface Transportation Policy and Revenue Study Commission authorized in Section 1909 of SAFETEA-LU. The papers are intended to synthesize the state-of-the-practice consensus on the issues that are relevant to the Commission's charge outlined in Section 1909, and will serve as background material in developing the analyses to be presented in the final report of the Commission.

This paper presents information on how climate change may impact transportation infrastructure and services. It provides consensus information on how the climate is changing based on primary sources such as reports by the International Panel for Climate Change and the National Research Council's Committee on Climate Change Science, and summarizes existing literature on how such changes might impact transportation. It also provides early results of the Gulf Coast Study which is the most detailed examination of this topic to date. The *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure – Gulf Coast Study* is a major, multiphase research effort undertaken by the U.S. DOT in partnership with the U.S. Geological Survey (USGS) to investigate the potential impacts of climate variability and change on transportation systems.

### Background and Key Findings

- The climate is changing. The planet is getting warmer which is causing sea levels to rise and creating disruptions in the hydrologic cycle. While some of these climate effects are not well specified at present, others are.

- Impacts to the existing transportation infrastructure and services are potentially very significant in vulnerable regions. Given that infrastructure can last for a century or more and that siting decisions made today may affect the resilience of future transportation networks, these impacts are worthy of consideration. There are likely funding and investment impacts from considering these impacts as well as failing to consider them.

- Climate change will have different impacts in different regions. Impacts in northern latitudes will differ from those in southern latitudes. Each region has to assess these impacts independently.

- The potential impacts of climate change cannot be divorced from the existing natural environment and anticipated changes within it. Sea-level rise, for example, cannot be assessed without consideration of land elevations. There are areas of the country, particularly in the Gulf Coast, where impacts associated with the natural environment – absent climate change – might be better addressed.

- It is possible to use climate data to assess the robustness and resilience of a region's transportation infrastructure. While the information needs of the transportation community must be better integrated with the data output of climate scientists, there is benefit to taking the long view on where to site new transportation facilities, and how to construct them to maximize their resilience.

- Continued research and assessment is necessary to maximize results from this type of analysis. The analysis of the potential impacts of climate change on transportation is still in its infancy. Greater benefits will result from continued examination.

## The Climate Is Changing

While much has been made of the uncertainties associated with climate change, there is a great deal that is known and for which scientific agreement exists.[1] First, the natural "greenhouse" effect is real, and is an essential component of the planet's climate process. Naturally occurring greenhouse gases effectively prevent part of the heat radiated by the Earth's surface from otherwise escaping to space. In the absence of these greenhouse gases (GHGs) the temperature would be too cold to support life as we know it today.

There is also agreement that carbon dioxide is a greenhouse gas that traps heat, and its concentration in the atmosphere has been increasing since the industrial age due to the combustion of fossil fuels and the burning of forests. Direct atmospheric measurements made over the past 50 years have documented the steady growth in carbon dioxide concentrations. In addition, analysis of air bubbles trapped in ice cores show that atmospheric carbon dioxide has increased by more than 30% since 1750. Other heat-trapping gases are also increasing as a result of human activities. Once in the atmosphere these greenhouse gases have a long life-time, on the order of decades to centuries, which means that they will warm the atmosphere for a long time even if reductions are made.

Scientific consensus on climate change has grown rapidly in recent years as advances in analysis have been achieved. The reality of climate change – and the anthropogenic influences on that change – are now broadly accepted by both national and internationally-recognized scientific organizations and governments. Dr. James Mahoney, former Assistant Secretary of NOAA and Director of President Bush's Climate Change Science Program testified before the Senate Environment and Public Works Committee in July 2005. He stated, "We know that an increase in greenhouse gases from the use of energy from fossil fuels and other human activities is associated with the warming of the earth's surface."

***Temperature has increased and is projected to continue to do so.*** The US temperatures have been rising over the last century, with more rapid increases since 1970 than earlier. Some of this change is likely due to natural variability and some of it is likely due to anthropogenic causes.

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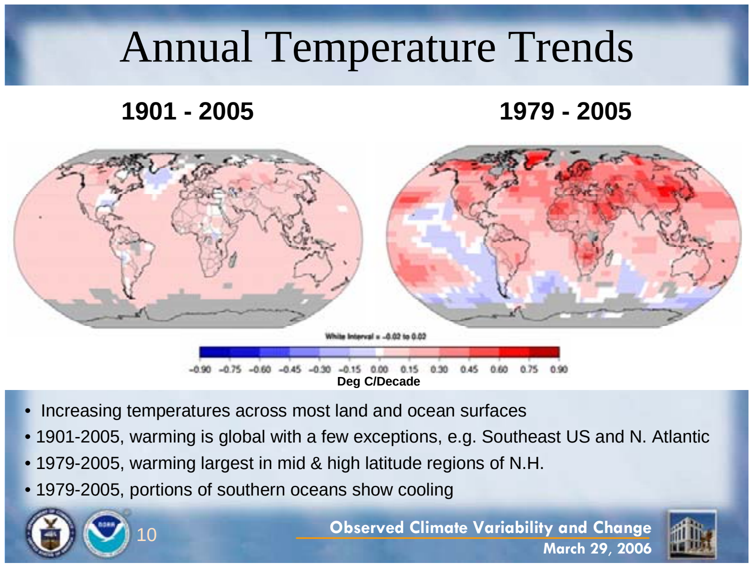
[1] Primary sources supporting this discussion are *Climate Change 2001: The Scientific Basis,* a report by the International Panel for Climate Change, and *Climate Change Science: An Analysis of Some Key Questions,* a 2001 report by the National Research Council's Committee on the Science of Climate Change.

The last major challenge to whether the planet was warming or not was resolved in April 2006 with publication of, "Temperature Trends in the Lower Atmosphere" (US Climate Change Science Program, Synthesis and Assessment Product 1.1, 2006). This study prepared in cooperation with noted critics of climate change science reconciled the remaining differences between surface and satellite temperature readings.




Generally the climate models that attempt to estimate temperature changes under future climate scenarios agree that it will be warmer in the future. The International Panel on Climate Change (IPCC) estimates that the global temperature will warm between 2.5°F and 10°F by 2100 on average. This is the result of reviewing a robust set of global climate models under a variety of future scenarios for the earth as a whole. The IPCC analysis integrates widely varying regional responses where the impacts would range more broadly. The average increase in temperature may not be as important to the transportation community as the changes in extreme temperature which are also expected to increase. The number of days with temperature above 90°F and 100°F has been increasing since 1970.

For examples of what may occur in the future, NOAA analyzed the temperature patterns for Dallas, TX. Their analysis shows that the probability of a having five days with a high of 110°F in one summer will rise to 30% in 50 years. Currently, the probability is only about 2%. Dallas did not actually reach 110°F even once in any of the last three summers (June, July and August of 2004-2006). That chance rises to over 90 percent by 2100.

***Precipitation projections are ambiguous but heavy precipitation events have increased.***
It is not clear whether precipitation will increase or decrease in the future. There is no clear trend in the existing precipitation data. Furthermore, the models disagree about whether the future will be wetter or drier under future climate scenarios. There will likely be region-to-region variations where some regions may get more precipitation and others less. While the total amount of future precipitation for most regions is quite uncertain, there are a few aspects of precipitation that have greater certainty, such as increases in heavy precipitation, and a shift from snow to rain in a warming climate.

According to NOAA analyses, the magnitude of the highest precipitation events has been increasing since 1970. A Simple Daily Intensity Index which examines the total precipitation for the US divided by the number of days with precipitation demonstrates an increase in average intensity from 1970 to 2005. These observed increases in heavy precipitation events are in keeping with empirical analyses and model projections for the future. While this is an area of continued discussion within climate science, there is a growing body of literature that indicates a future of more intense storms.

***Sea-level is rising and the rate of change is accelerating.*** As the earth warms, two changes are occurring that are causing global sea levels to increase: glacial melting and thermal expansion of the oceans. Sea-level rise is perhaps the best documented and most accepted impact of climate change. Sea-level trends were examined by the US National Assessment on Coastal Areas and Marine Resources. They found that since 1900, sea level was rising although not uniformly due to the net effect of vertical movement of land and coastal erosion patterns in that location combined with changing sea levels. If the land is rising, the relative sea-level rise will not be as great or may even decline. For example, sea-levels were found to be rising in San Francisco, Key West, Baltimore, New York City and Galveston between 1900 and 2000, but relative sea-level in Sitka, AK appears to be decreasing for the reasons cited above.

Most of the projected sea-level rise is due to thermal expansion of the oceans, but some is due to the melting of ice sheets. Should the melting of the polar ice caps accelerate, sea-level would rise much higher. For example, if the Greenland ice sheet were to melt, global sea level would rise over 21 feet which would prove disastrous for coastal areas and many major cities.

***The number of intense storms is expected to increase.*** The link between global climate change and the number and/or intensity of tropical storms is still being debated. Nevertheless, there is solid theoretical and model analysis that indicates that warmer oceans will provide more energy resulting in stronger storms. This means that the frequency with which an area is hit with a Category 3, 4 or 5 hurricane is likely to increase as the climate warms.

There are several aspects of storms that are relevant to transportation: precipitation, winds and wind-induced storm surge. All three tend to get much worse during strong storms. Strong storms tend to have longer periods of intense precipitation and wind damage increases exponentially with wind speed. The primary concern with hurricanes is for strong storms of Categories 3, 4 and 5. These storms have a lot more destructive energy. A Category 5 storm may have winds twice as fast as a Category 1 storm, but its kinetic energy is over 4 times greater.

## Overview of the Potential Impacts on Transportation – Recent Studies

That the climate is changing leads to a number of intriguing and critically important questions. First, the transportation community -- the planners, engineers, builders, operators, and stewards of our Nation's roads, airports, rail, transit systems, and ports – is increasingly concerned with the question of how such changes will affect the trillions of dollars of investment this infrastructure and associated services represent. Nationally, we invest about $100 billion annually in highways and transit alone. Add to this the considerable investment made by the private sector in freight rail, airports and ports, and it is clear that the value that we place on these systems is enormous. Any disruption to the timely delivery of goods and services can have immediate impacts ranging from the annoying, such as flight delays due to severe weather, to the catastrophic, such as the chaos wrought by Hurricanes Katrina and Rita.

A review of the literature supports the conclusion that the potential impacts of climate on transportation may be significant and are geographically widespread, modally diverse, and may affect both transportation infrastructure and operations. The impacts addressed most frequently are: increasing temperatures, changing precipitation, rising sea levels, and changes in storm activity. A summary of the literature findings regarding these impacts, and their corresponding adaptation measures, is presented below.

***Increasing Temperatures*:** Increasing temperatures have the potential to affect multiple modes of transportation. The transportation impacts mentioned most often in the literature included rutting, cracking, bleeding and potholing of highway asphalt; rail buckling; and the implications of lower inland water levels, thawing permafrost, and less ice cover.

The quality of highway pavement was identified as a potential issue for temperate climates, where more extreme summer temperatures and/or more frequent freeze/thaw cycles may be experienced. Extremely hot days, over an extended period of time, could lead to the rutting of highway pavement and the more rapid breakdown of asphalt seal binders. This, in turn, could damage the structural integrity of the road and/or cause the pavement to become more slippery when wet.

Railroads could encounter rail buckling more frequently in temperate climates that experience extremely hot temperatures. If unaddressed, rail buckling can result in derailment of trains, lower speeds and shorter trains, to shorten braking distance, and lighter loads to reduce track stress, raising shipping costs significantly.

Changes in water levels were discussed in relation to marine transport. Inland waterways could experience lower water levels, due to increased temperatures and evaporation; lower water levels would mean that ships and barges would carry less weight.

Reduced ice cover was generally considered a positive impact of increasing temperatures. For example, a study conducted by Lindeberg and Albercook, which was included in the Report of the Great Lakes Regional Assessment, stated, "the costs of additional dredging could be partially mitigated by the benefits of additional shipping days on the [Great] Lakes caused by less persistent ice cover." Additionally, arctic sea passages could open; the Arctic Climate Impact Assessment noted, "projected reductions in sea-ice extent are likely to improve access along the Northern Sea Route and the Northwest Passage."

The implications of melting permafrost for arctic infrastructure receive considerable attention in the literature. Permafrost is the standard natural foundation upon which much of the Arctic's infrastructure is built. The literature consistently noted that as the permafrost thaws the infrastructure will become unstable – an effect being experienced today. Roads, railways, and airstrips are all vulnerable to the thawing of permafrost. According to the Arctic Research Commission, "roads, railways, and airstrips placed on ice-rich continuous permafrost will generally require relocation … or replacement with substantially different construction methods."

***Changing Precipitation*:** Increases in the intensity of precipitation events could impact roads, bikeways/walkways and rail beds. Increased flooding could temporarily disrupt passenger travel either on roadways or transit and cause subsidence and heave of embankments, ultimately resulting in landslides. Adaptation measures included monitoring infrastructure conditions, preparing for service delays or cancellations, and replacing surfaces when necessary. Although mentioned less frequently, some attention was given in the literature to bridge scour from increased stream flow. Bridge scour could cause abutments to move and damage bridges.

***Rising Sea Levels***: Sea-level rise could affect all modes of transportation seriously in areas of low elevation. Low-level roads and airports are at risk of inundation, and ports may see higher tides. Titus concluded "the most important impact of sea-level rise on transportation concerns local roads. In many low-lying communities, roads are lower than the surrounding lands, so that land can drain into the streets. As a result, the streets are the first to flood." Adaptation measures include relocation, and the construction of flood defense mechanisms (such as dikes), as well as more frequent maintenance (Titus, 2002). Although mentioned less often in the literature, deeper water caused by sea-level rise could permit greater ship drafts.

***Storm Activity***: Storm activity was discussed as an issue, impacting both inland areas and coastal areas. Impacts most frequently mentioned in the literature include storm surges that could potentially cause damage to coastal areas, and a decrease in winter snowstorms (with more winter precipitation falling as rain).

In coastal areas, increased storm activity or intensity could lead to an increase in storm surge flooding and severe damage to infrastructure, including roads, rails, and airports. These effects could be exacerbated by a rise in sea level. In addition, coastal urban areas, like New York City, could potentially see storm surges that flood the subway system. As Zimmerman noted, "transportation systems are traditionally sited in low-lying areas already prone to flooding." She went on to state that, "New York City alone has over 500 miles of coastline, much of which is transgressed by transportation infrastructure – roadways, rail lines, and ventilations shafts, entrances and exits for tunnels and transit systems, many are at elevations at risk of being flooded …."

A decrease in winter snow storms could potentially relieve areas that typically see large amounts of snow from some of the cost of maintaining winter roads. Natural Resources Canada concluded, "if populated areas were to receive less snowfall and/or experience fewer days with snow, this could result in substantial savings for road authorities."

## The Gulf Coast Study

As the question of impacts and adaptation is an emerging field for researchers, the existing literature has little to offer transportation planners in whether the potential impacts to a given area are severe enough to warrant additional investment in the local transportation network. Most current studies lack specificity about what climate changes may bring to a region of the US, the magnitude of change to a region's transportation system, and how that area might adapt to make the network more robust. These questions led DOT to work with the USGS to develop the Gulf Coast Study, one of just 21 “priority” projects under the President’s Climate Change Science Program.

The following results are taken from interim working papers developed for the Gulf Coast Study. They address likely impacts relating to the most certain climate changes regarding sea-level rise, storm surge, temperature increases and changes in precipitation. As the report is not yet final, results reported here should be considered preliminary.

***Sea-Level Rise* –** Sea level in the Gulf Coast is rising faster than the general rate of increase in many other areas. This is because the land is sinking (subsiding) for geological and other reasons. Based on our analysis of possible future scenarios (using three different emission scenarios and 19 different models), it is very likely that sea level will rise two to four feet in the next 50 to 100 years. Absent other mitigation strategies, this would have a devastating impact on the highway infrastructure in the area. Based on land elevations, a four-foot increase in sea level will inundate about one-quarter of the major roads (24 percent of the Interstate Highway miles and 28 percent of the arterial miles) in the region. Because of their location, this rise will also affect 43 percent of the Intermodal connector miles and New Orleans Transit. About three-fourths of all ports will be flooded, but only nine percent of the rail miles since many of them are at higher elevation. Without adaptive actions to address this in the future, this will be a permanent flooding.

***Storm Surge* –** As witnessed during Hurricanes Katrina and Rita, the existing infrastructure in the Gulf Coast is quite vulnerable to storm surge. This is very likely to become worse in the future. An analysis of the frequency of Category 3, 4 and 5 hurricanes making landfall shows that a storm of this intensity will strike the Gulf Coast every 22 years on average (allowing for natural variability). This return rate will decrease to about 18 years on average, resulting in more frequent hurricane strikes.

Category 3 storms and higher cause different levels of storm surge depending on other conditions. Storm surges of 18 to 23 feet are not uncommon for this level of hurricane. Katrina had a storm surge of 25 feet at landfall. Analysis in the Gulf coast shows that almost two-thirds (64 percent) of all Interstate highway miles are subject to temporary flooding due to a storm surge of 18 feet. Similarly, 41 percent of rail miles and virtually all ports (99 percent) are subject to temporary flooding at this level of surge.

The Gulf Coast Study has not yet examined the infrastructure for potential damage due to this level of surge. However, those facilities subject to flooding are likely to face increased risk of damage from storm surge as well, due to collision with the surge as well as from displaced vehicles, trees and other debris striking or encumbering the infrastructure. The net impact of damage due to hurricanes will increase as barrier islands are washed away and sea-level rises.

***Temperature* –** All the models under all of the scenarios that were examined agree that average temperatures in the Gulf Coast will increase one to seven degrees within the next 50 to 100 years. Of more importance to transportation is the increase in extreme temperatures. Consistent with the increase in average temperature, the Gulf Coast analysis indicates that the number of days above 90°F will increase by roughly 16 percent (from 77 to 89 days) and could be as high as almost 50 percent (from 77 to 115 days) in the next 50 to 100 years. This will likely result in increased maintenance needs for roads, ports and rail. Even though these impacts cannot be quantified, this level of increase would result in increased pavement wear and rail buckling. It will also likely result in increased costs of construction and use of energy for cold storage.

***Precipitation*** – The models used to analyze future precipitation in the Gulf Coast yielded conflicting results. Some models indicated that average annual precipitation would increase while others showed a decline. The inconsistency of model outputs for precipitation makes these projections of marginal value to transportation planners and service operators.
However, the potential for increased intensity of rainfall events poses concerns for the transportation community even if the overall average amounts of precipitation do not change. An increase in heavy downpours could overload highway drainage systems and increase operational and safety concerns. It could also force changes in the size of storm water treatment facilities at ports, and increase sub grade erosion of rail lines.

## Conclusions

The analysis of how climate change might affect transportation infrastructure and services is an emerging topic. In addition to the studies referenced above, the Transportation Research Board is conducting a major study on Climate Change and US Transportation. Results are expected in summer 2007.

While studies are ongoing, it is clear that climate change is a natural, continuous Earth process that is influenced by the concentration of greenhouse gases in the atmosphere. Human activity has increased the concentration of atmospheric $C0_2$ by more than 30% since 1750, which accelerated warming during the past century. While the precise contribution of human activity to climate change is debated, we know from the climate record that an increase in greenhouse gas concentrations is accompanied by an increase in the Earth's temperature.

As the Earth's atmosphere warms, the hydrologic cycle intensifies and sea-level rises due to thermal expansion and melt of continental land ice. Rainfall has increased approximately 10% in North America since 1900, but changes in rainfall vary widely among U.S. regions.

Impacts to the existing transportation infrastructure and services are potentially highly significant in vulnerable regions. Given that infrastructure can last for a century or more and that siting decisions made today may affect the resilience of future transportation networks, these impacts are worthy of consideration. There are likely funding and investment impacts from considering these impacts as well as failing to consider them.

Climate change will have different impacts in different regions, due to the heterogeneity of both the changes in climate and the types of impacts that will occur in the physical, biological and human systems that are unique to each region. Low-lying coastal zones, deltas, alpine areas, floodplains, and arid lands are also among the hotspots of vulnerability to climate change. Since climate change and its physical impacts vary widely among regions, effective adaptation strategies for the transportation sector will be tailored for specific regions as well as transportation modes.

The potential impacts of climate change cannot be divorced from the existing natural environment and anticipated changes within that environment. Sea-level rise, for example, cannot be assessed without considering land elevation and trends (like subsidence or uplift). In rapidly subsiding areas of the Gulf Coast, for example, impacts on transportation associated with natural environmental change are equally important considerations in developing adaptation strategies to future climatic change.

It is possible to use climate data to assess the robustness and resilience of a region's transportation infrastructure. While the information needs of the transportation community must be better integrated with the data output of climate scientists, there is benefit to taking the long view on where to site new transportation facilities, and how to construct them to maximize their resilience in the development of a robust network.

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## CONSOLIDATED COMMENTS FROM MEMBERS OF THE BLUE RIBBON PANEL OF TRANSPORTATION EXPERTS - PAPER 4D-01

One reviewer commented as follows:

Global warming is an enormously complicated and controversial topic. This reviewer would suggest that the crux of the problem is that, beyond agreement that the earth is getting warmer and at least some of that warmth is caused by human activities, much surrounding climate change is not yet clear. This suggest that it would be more useful if the paper made more liberal use of "if, then" statements.

On page 5 the paper states: "Railroads could encounter rail buckling more frequently in temperate climates that experience extremely hot temperatures. If unaddressed, rail buckling can result in derailment of trains, lower speeds and shorter trains, to shorten braking distance, and lighter loads to reduce track stress, raising shipping costs significantly." It is true that extreme heat occasionally causes rail to warp, leading to derailments if not corrected. But the problem is not widespread — over the past 4 years, these "sun-kinks" were a primary or secondary cause of 129 accidents, or 1% of total rail accidents — and, given the way rail is constructed, installed, and maintained, there would likely have to be a truly phenomenal increase in temperatures to have a material increase in the number of sun kinks. (If temperatures increased to that degree, sun kinks would probably be among the last things our society, or at least what would be left of it, would worry about.) Even if one accepts, for sake of argument, that global warming will cause temperatures to increase so much that there will be a material increase in cases of sun kinks or other heat-induced rail-related problems, railroads would not sit idly by while their operations disintegrated. They would address the problems.

And that is only one side of the coin. If one accepts that global warming will make extreme heat so much more frequent that it will lead to substantially more sun kinks and a material reduction in rail fluidity, etc., one must also accept that global warming will make extreme cold weather more moderate. This could have substantial *positive* consequences for transportation in general and railroads in particular. For example, extreme cold can cause rail to become brittle and break.

Snowstorms can shut down rail networks across entire regions. Snow and ice accumulations can occur in rail switches, brake riggings, track components, and grade crossings, thereby reducing control and increasing the risks of derailments and other types of incidents. Freeze-thaw cycles can damage track and terrain. Cold weather inhibits the performance of diesel locomotives. By the same logic that says that global warming would have negative effects on railroads, global warming would also reduce the cold and ice impacts noted above, thereby positively contributing to more efficient, safer rail operations.